Resilience framework for seaport infrastructure: theory and application

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A. Balbi & M. P. Repetto
University of Genoa, Italy

O. Kammouh & G.P. Cimellaro
Politecnico di Torino, Italy

ABSTRACT: The efficient movement of goods is crucial to the economic growth of communities. This makes the existence of seaports essential for the marine transportation system. Due to their natural location, ports are continuously threatened by natural hazards such as wind action, which necessitates a continuous monitoring and assessment for their performance. The work presented here aims at assessing the resilience of ports against natural disasters. This is done by identifying the performance and the recovery rate of such infrastructure during the period following the event. The research commenced with gathering information about the port's main components that are influenced by natural hazards. The collected data has been compiled in the form of indicators, which have been filtered and grouped under four dimensions in the proposed "PORT framework". Each of the indicator has been allocated a *measure* to enable its quantitative evaluation. The aggregation of the indicators' values allows identifying the port resilience.

1 INTRODUCTION

Ports are a main component of the physical infrastructure of coastal communities. Despite their importance, they are often overlooked in the disaster resilience engineering. Seaport infrastructure is fundamental for marine transportation at both local and national scales. Normally, ports are significantly exposed to natural and manmade disasters (Kron 2011), which necessitates assessing their resilience and performance in order to set mitigation plans for extreme disruptive events.

Although much effort has already been made to boost research on resilience measurement (Cimellaro et al., 2010), there is still no acceptable method for the evaluation of the resilience of large infrastructure systems like ports, and there are still challenges in developing real evaluation strategies.

Different kind of approaches are presented in the literature to measure the seaport resilience: some consider specific scenarios in their studies to measure the performance of given port components, such as the destruction of quays under a seismic event (Safieezadeh et al.2014), while others focus on identifying port performance indicators (e.g. number of TEU's (Twenty-foot Equivalent Unit), tons of dry and liquid bulk material (Pant et al. 2014), etc.), which are used to build performance evaluation frameworks (Berle et al. 2011, Baker et al 2013, Heinsen et al. 2014, Kurapati et al 2015, Mohd Salleh et al. 2015, Gharehgozli et al 2016, Mcintosh et al. 2017). Both kind of approaches have advantages and disadvantages. The first one considers a thorough investigation of a single problem but it does not capture the complexity of the different scenarios that may affect the activity of the port, like communication or organizational problems, and it often only tackles the resilience of structural elements of the port, like berth or cranes. The second approach, on the other hand, uses several generic indicators to determine the resilience of ports. The indicators are assessed independently at a given time without considering their interdependency. In this type of approaches, no final port resilience measure has been proposed in previous work and so the overall performance of the port has not been identified. Indeed, the existing resilience approaches do not actually measure the resilience but rather the performance of ports because resilience is a dynamic process that needs to be assessed for a given period of time following the perturbation and not only at a given instance of time.

The approach introduced in this paper fulfills the mentioned shortcomings by proposing a framework that covers all the significant aspects of port activities at both structural and organizational levels. The interdependency among the ports' elements is considered through the use of weighted indicators. The final output of the framework is a dynamic port resilience measure.

2 METODOLOGY

Measuring the seaport resilience under natural hazards such as wind actions is a challenging task. Although the use of indicators is perceived as an important instrument to measure resilience, developing a standardized set of resilience indicators is clearly challenging for such a dynamic, constantly reshaping and context-dependent concept.

Among the various resilience approaches in the field of engineering, the ones proposed by Bruneau et al. (2003) and Cimellaro et al. (2016) are the most suitable for developing a resilience framework for port infrastructure. For the purpose of this study, the resilience definition given by Bruneau (2003) is considered: resilience is “the ability of community units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways to minimize disruption and mitigate the effectors of further events”.

Kammouh et al. (2017c) proposed a novel method for evaluating community resilience. The method starts by collecting all community resilience indicators found in the literature and then allocating them into homogeneous components, classified under seven dimensions (Kammouh et al. 2017c, Kammouh et al., unpubl). A measure is assigned to each indicator allowing it to be quantified. The measure is not represented by a scalar value but rather a normalized continuous function that marks the serviceability of the community in time (Figure 1). All measures are weighted according to their contribution in the overall resilience assessment. The methodology takes as inputs the indicators’ serviceability before and after a

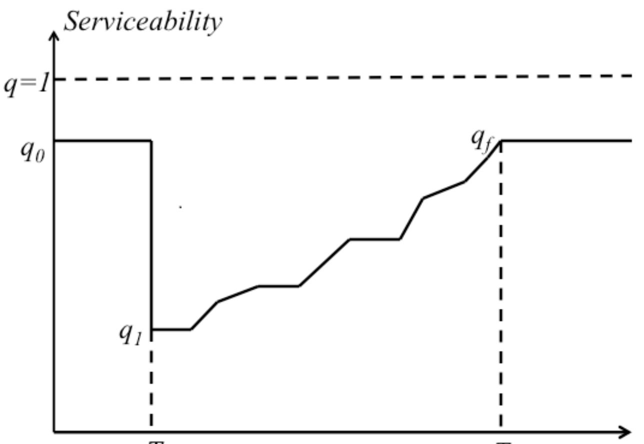

Figure 1. The concept of Serviceability function: q_0 initial serviceability, T_1 disaster event time, q_1 post-disaster serviceability, q_f final serviceability after T_R

given hazard and turns as an output the serviceability curve of the community as well as a resilience measure. The resilience is then computed as the area under the serviceability function for a defined control time (T_1 -T_f) following the disaster (Figure 1).

The method proposed in this paper is inspired by the work previously done in (Kammouh et al. 2017c) as it uses the same algorithm. However, a new and exhaustive list of indicators that are applicable only for port infrastructures is introduced in this paper.

The identification of a set of port-specific indicators was fundamental for identifying the main ports elements that could be influenced by the natural hazards. This task has been completed through a wide literature research on port indicators and several visits to the VTE (Voltri Terminal Europa), the main container terminal of the Port of Genoa and one of the most important in the Mediterranean area. The collected data have been compiled in the form of *indicators*, which have been filtered and classified under a set of *components*. Finally, the components have been grouped under four *dimensions*: Physical Infrastructure, ICT and Equipment; Organization and Business Management; Resources and Economy Development; and Territory, Environment and Stakeholders, summarized under the acronym “PORT” (Table 1). Each indicator has been assigned a measure to make it quantifiable and then weighted according to its interdependency with the other indicators.

Table 1 Dimensions and components of the PORT framework

Physical Infrastructure, ICT and Equipment	**Resources and Economy Development**
1.1 Quay Cycle	3.1 Financial Flows
1.2 Trucks Cycle	3.2 Financial Services
1.3 Rail Cycle	3.3 Port Business and Costs
1.4 Yard	3.4 Employment Services
1.5 Port Buildings	
1.6 Containers	
1.7 Port Utility Services	
1.8 Technical Services Availability	
Organization and Business Management	**Territory, Environment and Stakeholders**
2.1 Terminal Policy	4.1 External Physical Access
2.2 Internal and External Communication	4.2 Environment Sustainably
2.3 Human Resources	4.3 Reputation
2.4 Resources Planning	
2.5 Risk Assessment and Mitigation	
2.6 Preparedness, Response and Recovery	

Several weighting techniques exist in the literature (Kammouh et al. 2017a, Kammouh et al., 2017b, Kammouh et al. 2017c). At this stage, the weighting factors are assumed in the range between 1 and 3 on the basis of qualitative judgment. Future work will be addressed to a quantitative definition of such factors Table 1 lists the dimensions and the components of the PORT framework.

3 PORT FRAMEWORK STRUCTURE

Figure 2 shows a simple scheme of the port areas and the principal activities that are adopted in this work as indicators. Three cycles (train, quay and trucks cycles), the yard and the buildings are the main intermodal areas of the Port, where the most important activities are carried out. Containers are moved from the Quay Cycle to the Yard and to the Trucks and Train Cycles in order to be shipped through the external Railway and Roadway System and vice versa.

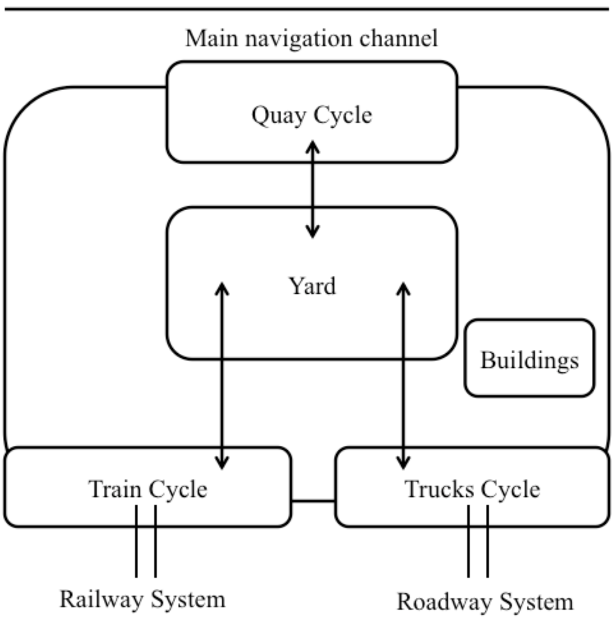

Figure 2. Schematic representation of different port area ort Areas and their interconnections.

A full list of dimensions, components, and indicators can be found in Appendix. In this table, a measure has been assigned to each indicator to allow its quantitative evaluation. The measures have been defined in close collaboration with the port experts to insure that the proposed data actually exists in the port terminals databases.

TV is the "Target Value" of the indicator, usually defined by the terminal experts and safety&security manager. This quantity is used as a baseline to normalize the measures. For instance, if we consider the measure "Quay gantry cranes low profile (indicator 1.1.1 in Appendix), the output of the measure would be *the daily number of TEUs handled by port cranes low profile type*. The output in its current shape can not be combined with other measures until it is normalized. This is done by dividing over the corresponding *TV*. In this case, *TV* represents the *ideal number of TEUs that the crane can handle as expected by port operators*. This operation (normalization) allows comparing and considering different heterogeneous variables related to different port aspects, such as physical infrastructure, port communications and the economic resources

I is the importance factor of each indicator which is determined according to the indicator's contribution in the overall resilience assessment.

Nat describes the nature of the indicator: The indicators can be either Static (*S*) or Dynamic (*D*). Static indicators are the ones that are not affected by the disastrous event and their values do not change after the disaster, while Dynamic indicators are the ones whose values change after the disaster's occurrence.

In the following, each dimension with selected components (in **bold**) and indicators (in *italic*) are described in details.

3.1 *Physical Infrastructure, ICT and Equipment;*

Eight components are considered to describe this dimension: **Quay Cycle**, **Trucks Cycle**, **Train Cycle**, **Yard**, **Port Buildings**, **Containers**, **Port Utility systems** and **Technical Services Availability**. The first four components represent the areas where the most important operations of the port take place. The critical elements needed to run the operations in the mentioned port areas have been investigated. The "crane" has been spotted as the most critical element to run most operations in the different port zones. That is, in case of crane interruption, most port activities break in.

In the **Quay Cycle**, cranes are placed on rails near the dock for loading and unloading goods from the ships. Their configuration is designed to meet specific height limits, especially when the port is close to an airport. Two different crane types are considered: *quay gantry cranes low profile type* and *quay gantry cranes gooseneck type*. These two types of cranes are therefore chosen as indicators for the Quay Cycle component.

Figure 3. VTE's quay gantry cranes - gooseneck type

In the **Trucks Cycle**, which is the area where the containers are loaded and unloaded to and from the *trucks*, there are the *rubber-tired gantries (RTGs*), which are mobile gantry cranes mounted on rubber tired used to stack the containers in the yard

In the **Train Cycle**, cranes are placed near the railroad tracks of the port area. They are defined as *Rail-Mounted Gantries cranes* and they are equipped with tracks in order to move easily along the length of the *freight train*.

In the **Yard**, to facilitate the internal container storage movements, cranes can be mounted both on Rubber or Rail as *Rubber-tired gantries* and *Rail-Mounted Gantries* respectively. For each of these elements, the most representative measure is "the daily number of congested containers". This measure applies to both loaded and unloaded containers. In addition, the two elements: *Prime Mover* and *Reach Strakes* are necessary for the internal movement in the terminal area (i.e., to move the TEUs from one cycle to another or to carry them to the rubber vehicles in the storage yard) and therefore they are chosen as additional indicators.

Figure 4. The Yard with the rubber-tired gantries and rail-mounted gantries

Buildings serviceability is determined according to their resistance. An event that significantly reduces the building capacity implies the building's closure or destruction, with consequences on both the human life and the port activity.

The **Containers** are fundamental for organizing the entire port activity. Containers can be stored in temperature controlled environments and they can be either empty or full. *Empty container,* in particular, is chosen as an indicator for the **Containers** component due to their critical role during emergencies, where the goods in the damaged containers are moved to the empty ones. Other indicators for this component can be found in Appendix.

The **Utilities,** such as *gas* and *electricity*, are critical for the operation of the port cranes. *Electricity* is crucial also for the operation of *ICT* equipment (informational and communication technology), which is essential for the internal management of the port handling and storage.

The availability of **Technical Services** facilities represent a main component to run the port activities. If these services are absent or unavailable, the entry of ships into the dock becomes more complex or even impossible. Therefore, **Technical Services** has been chosen as a component for this dimension.

3.2 *Organization and Business Management;*

Port Organization activity components are divided into two main categories: ordinary organization practices and extraordinary organization practices. Ordinary organizational practices are: **terminal policies**, **internal and external communications**, **human resources**, and **resources planning**. Extraordinary organizations are related to **risk assessment and mitigation**, **response preparation and reconstruction**.

Terminal Policy: considers the *Health and Safety Executive* (HSE), which measures the effect of the perturbation on the workers' safety and health. It also considers the serviceability of the *Informational Technology system,* which plays a central role in the port main activities (e.g. the operation of the *cranes)*. For example, a computer system block can lead to the immediate cessation of all port activities as it becomes impossible to know the location, destination, and contents of the containers. It is measured with "the number of *IT* block events that cause the port activities to stop". Another indicator is the *Terminal security*, which depends on the ISPS code (International Ship and Port Facility Security Code). Destructive events cause the terminal security to be weakened as the level of control is reduced.

Internal and external communication plays an important role in the port organization serviceability. One of the most weighted indicators for this component is the *internal terminal communication indicator* (location, destination, and container contents), known as EDI connectivity (Electronic Data Interchange).

The component **Human resources** is divided into four indicators: *operational personnel*, *staff planning operational activities*, *supervisory staff* and *Manning of Dockers*. In the scenario of a destructive event, the *operational personnel* indicator becomes particularly sensitive due to the fluctuation in the amount of work carried out.

Resources Planning: concerns the *Berth Window occupancy delays*, the average permanence of a container within the yard (*Turnaround Time*) and the *berth occupancy rate*.

The second part of the components related to this dimension concern the **assessment and mitigation of risks** and the **preparation and allocation of resources** to mitigate the effects of the disaster event. These components are present in Appendix but are not described in the paper.

3.3 *Resources and Economy Development*

Ports usually require good **Financial Flows** to allow the investments in port activities. For ports, investments are fundamental to ensure their competitiveness and serviceability. Measuring the financial flow is crucial in order to evaluate the serviceability of a port system and its potential to expand and develop. Investments for which a capital is required may be of several types, superstructures such as cranes, maintenance and drainage, and expansion of the storage space. An additional effect of the destructives event on the financial capabilities of a port is the difficulty to access the *Financial Services.*

The **Port business** component is related to those indictors through which the economic outlook of a port is commonly assessed. The most relevant indicator for **port business** is the number of containers (*tonnage*) that is handled annually by the port.

3.4 *Territory, Environment and Stakeholders*

In this last component, the port elements that are located outside the port terminal are considered: the **access routes** to the port terminal, the quality of the environment **(environment sustainability)** and the port's social **reputation**. The first component concerns the serviceability of access roads such as the *highway access infrastructure*, the *incoming rail,* and the *navigation channel* through which ships depart and arrive. The environmental sustainability of the port activity includes the *quality of air, water* (can be reduced by ship spills), and *noise pollution,* which can have a strong impact on the surrounding citizenship.

The impact of the port activity on the citizens' lives may seriously affect the *port's social image*. This indictor is of special importance to the port terminal operators as it can lead to the closure of port activities in extreme cases.

4 CONCLUSION

This paper introduces a resilience measurement tool for seaports. The introduced PORT framework consists of a large number of resilience indicators that cover the main aspects of a port activity and management. A wide literature review has been made and several port experts and port authority personnel have been interviewed in order to conclude the presented indicators list.

Future work aims at defining quantitatively the weighting factors and validating the proposed framework by applying it to a real case study, such as the Genoa port. A user-friendly software tool in which the above methodology is implemented will also be introduced.

5 ACKNOWLEDGMENT

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APPENDIX

Dimension/ component/indicator	Measure (0 ≤value ≤1)	Ref	I	Nat
1. Physical Infrastructure, ITC, Equipments			3	
1.1 Quay Cycle			3	
- Quay gantry cranes low profile type	Daily n° of TEUs loaded and unloaded ÷ TV	Morris 2017 Thoresen 2003	3	D
- Quay gantry cranes gooseneck type	Daily n° of TEUs loaded and unloaded ÷ TV	Morris 2017 Thoresen (2003)	3	D
1.2 Trucks Cycle			3	
- Trucks	Daily n° of Trucks Served ÷TV	Soutworth et al.2014	2	D
- Rubber-tired gantries (RTG)	Daily n° of TEUs loaded and unloaded ÷ TV	Morris 2017 Thoresen 2003	3	D
1.3 Train Cycle			3	
- Trains	Daily n° of Train operated ÷ TV	Soutworth et al.2014	3	D
- Rail-mounted gantries	Daily n° of TEUs loaded and unloaded ÷ TV	Morris 2017 Thoresen 2003	3	D
1.4 Yard			3	
- Rubber-tired gantries	Daily n° of TEUs loaded and unloaded ÷ TV	Morris 2017 Thoresen 2003	3	D
- Rail-mounted gantries	Daily n° of TEUs loaded and unloaded ÷ TV	Morris 2017 Thoresen 200)	3	D
- Reach Stackers	n° of Reach Stackers available ÷ n° of Reach Stackers needed	Morris 2017	2	D
- Prime mover	n° of prime mover available ÷ n° of prime mover needed	Morris 2017	2	D
1.5 Port Buildings			3	
- Docks	Resistance of the structure	Soutworth et al.2014 Thoresen 2003	3	D
- Administration buildings office	Resistance of the structure	Soutworth et al.2014	2	D

- Operation Control Room	Resistance of the structure	**	3	D
- Maintenance buildings	Resistance of the structure	**	1	D
- CFS	Resistance of the structure	Na&Shinozuka 2009	3	D
1.6 Containers			3	
- IMO Goods	n° of IMO TEUs handled ÷ n° of TEUs demanded, per cycle	**	2	D
- Reefer	n° of Reefer TEUs handled ÷ n° of TEUs demanded, per cycle	Soutworth et al.2014	2	D
- Empty Containers	n° of undamaged empty TEUs handled÷ n° of empty TEU's demanded, per cycle	**	3	D
- FCL	n° of FCL handled ÷ n° of TEUs demanded, per cycle	Soutworth et al.2014	3	D
1.7 Port Utility Systems			2	
- Power line/Electricity sub-station	KW/h provided to the port's cranes and equipment÷ KW/h needed	Beker et al. 2015	3	D
- Liquid fuel system	l of Liquid fuel provided to the yard equipment÷ l needed	Pitikilis 2011	3	D
- Fiber Optics	1 (if it is active), 0 (otherwise)	Beker et al. 2015	2	D
- Phone lines	1 (if it is active), 0 (otherwise)	Beker et al. 2015	1	D
- Sewer lines/(waste water system)	1 (if it is active), 0 (otherwise)	Beker et al. 2015	1	D
- Water utility	1 (if it is active), 0 (otherwise)	Beker et al. 2015	1	D
- Fire-fighting plant	1 (if it is active), 0 (otherwise)	Pitikilis 2011	1	S
1.8 Technical Services Availability			1	
- Pilots	1 (if it is active), 0 (otherwise)	Beker et al. 2015	2	D
- Thug Boats	1 (if it is active), 0 (otherwise)	**	2	D
- Mooring	1 (if it is active), 0 (otherwise)	**	2	D
Organization and Business Management			3	
2.1 Terminal Policy			3	
- HSE	n° of monthly professional Illnesses ÷ TV	de Langen et al. 2007*	1	S
- IT Policy	n° of monthly events stopped operations ÷ TV	Hsieh et al. 2013*	3	S
- Security organization (ISPS Code)	n° of monthly security incidents ÷ TV	de Langen et al.2007	2	S
- Delegation of authority	1 (if there is), 0 (otherwise)	de Langen et al.2007	1	S
2.2 Internal and External Communication			2	
- Terminal and Shipping Companies Communication	1 (if there is), 0 (otherwise)	Berle et al. 2011	2	S
- Terminal and Port Authority Communication/Coast Guard	1 (if there is), 0 (otherwise)	Berle et al. 2011	1	S
T- erminal and Trucks Company Communication	1 (if there is), 0 (otherwise)	Berle et al. 2011	2	S
- Terminal/Shipper&Forwarders Communication	1 (if there is), 0 (otherwise)	Berle et al. 2011	2	S
- Internal Terminal Communication (EDI connectivity)	1 (if there is), 0 (otherwise)	de Langen et al.2007	3	S
2.3 Human Resources			2	
- Availability of ops staff	n° of ops personnel available/ n° personnel needed for each enabling	Berle et al 2011*	3	D
- Planning of ops staff	n° of personnel supervising terminal÷ TV	Berle et al 2011*	2	D
- Supervising of ops staff	n° of personnel responsible for managing and performing transloading operations ÷ TV	Berle et al 2011*	2	D
- Manning of Dockers (to cover peaks)	n° of Manning of Dockers personnel available÷ n° personnel needed for each enabling	Berle et al. 2011*	2	D
2.4 Resources Planning and Location			2	
- Delays	1- ((n° of ships arrived at port at the berthing window - n° of ship allowed to enter into the port) ÷ n° of ships arrived at port)	Baker 2015	2	D
- Turnaround time	days of average warehousing of TEUs÷ TV	de Langen et al.2007	2	D
- Berth occupancy rate	n° of ships ÷ n° of quay available location	de Langen et al.2007	2	D
2.5 Risks Assessment and Mitigation			3	
- Policy/Risk appetite definition/Targets	1 (if there is), 0 (otherwise)	**	2	S
- Identification of hazards	1 (if there is), 0 (otherwise)	**	2	S
- Evaluation of risks	1 (if there is), 0 (otherwise)	**	2	S
- Mitigation countermeasures	% port area covered by a recent hazard mitigation plan	**	3	S

- Improvement Plan	% financial resources to carry out risk reduction activities ÷ TV	**	3	S
- Monitoring&Audit	% essential port elements that are under regular monitoring and audit programs	**	3	S
- Management review	1 (if there is), 0 (otherwise)	**	1	S
- Mitigation spending	Ten year average per m^2 spending for mitigation projects ÷ TV	Rose 2012	3	S
- Exposure to hazard protective resource	% building infrastructure not in high hazard zones	Cutter 2017	3	S
- Protective Resources	% of port area that consists of windbreaks/wave breaks	Cutter 2008	2	S
- Essential infrastructure resistance	% of essential structures that remained operational during emergencies in past events	UNISDR 2007	3	S
- Essential infrastructure assessment	% essential infrastructures that are under regular assessment programs	***	3	S
- Accuracy of building codes	% designed structural damage – % actual structural damage (from past events)	***	3	S
2.6 Preparedness, Response and Recovery			3	
- Terminal Emergency Response Plan	1 (if there is), 0 (otherwise)	**	3	S
- Training and drills of emergency squad	1 (if there is), 0 (otherwise)	**	2	S
- Accrual for crisis management supporting the restoration	1 (if there is), 0 (otherwise)	**	2	S
- Disaster risk reduction measures integrated into post-Disaster recovery and rehabilitation activities	1 (if there is), 0 (otherwise)	**	3	S
- Contingency plan degree including an outline strategy for post-disaster recovery and reconstruction)	1 (if there is), 0 (otherwise)	**	2	S
- Emergency external services	1 (if there is), 0 (otherwise)	**	2	S
- Crisis Communication Plan	1 (if there is), 0 (otherwise)	**	1	S
- Temporary facilities	1 (if there is), 0 (otherwise)	***	2	D
Resource and economic development			2	
3.1 Financial Flows			2	
- Access to capital and investment for dredging, safety measures and expansion	capital accessed/ capital needed	Berle et al. 2011	2	S
- Revenues, access to capital and liquidity to invest in warehouses, storage yards and connecting infrastructure	capital accessed ÷ capital needed	Berle et al. 2011	2	S
- Access to capital, liquidity and revenue to fund operations and investments in superstructure	capital accessed ÷ capital needed	Berle et al. 2011	2	S
- Access to capital, liquidity and revenue to fund operations and expansion of infrastructure	capital accessed ÷ capital needed	Berle et al. 2011	2	S
3.2 Financial Services			1	
- Difficulties in obtaining insurance	0 (if there are), 1 (otherwise)	***	1	S
- Hazard Insurance Coverage (Risks uninsurable)	% of port elements covered by insurance program	Cutter 2014	1	S
3.3 Terminal Business and Costs			3	
- Tonnage	total monthly of goods tons moved ÷ TV	Beker 2015	3	D
- Revenue to Terminal	monthly revenue to port ÷ TV	Beker 2015	3	D
- Operations continuity	1 (if there is), 0 (otherwise)	Beker 2015	3	S
- Respect of pre-storm business plans	1 (if there is), 0 (otherwise)	Beker 2015	1	S
I- nvestment growth	% of investment growth ÷ TV	***	3	D
Territory Envirorment and Stekeholders			2	
4.1 External Physical Access			3	
- Roadway Systems	1 (if there is), 0 (otherwise)	Pitikilis 2011	3	S
- Railway Systems	1 (if there is), 0 (otherwise)	Pitikilis 2011	3	S
- Main Navigation Channel	1 (if there is), 0 (otherwise)	Beker 2015	3	S
4.2 Environment Sustainably			2	
- Noise pollution	1-(noise pollution index (NPI) ÷ TV)	***	2	D
- Air quality	1-(air quality index (AQI) ÷ TV)	***	3	D
- Water Quality	1-(water quality index (WQI) ÷ TV)	***	3	D
- Waste management	1 (if there is), 0 (otherwise)	***	1	S
- Debris field cleaning	0 (if there is), 1 (otherwise)	***	2	S

4.3 Reputation		3	
- Social image of the port	1-(Social Image index (SII) ÷ TV)	3	D

* Indicator found in literature but strongly modified after meetings with port experts
** Indicator found after interviews with port experts and port authority personnel
*** Indicator proposed by the authors